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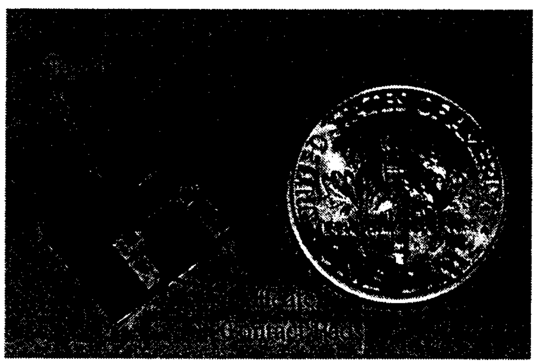

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Proof-of-concept testing of a microfabricated vaporizing liquid thruster was performed. In this liquid-fed thruster concept, propellant vaporization is achieved in a microfabricated thin film heater arrangement. Chip temperatures of 100, 150 and 200 C were achieved at power levels of 3.5, 5.5 and 7.5 W. Voltage requirements were below 5 V for these temperature values. A substantial fraction of the heat was believed to have been conducted into the packaging material. Thermal characterization tests of chips placed onto insulating Pyrex blocks resulted in temperatures of about 90 and 150 C for power levels of 1.2 and 2.5 W, respectively, thus cutting thermal losses by more than half. One thruster chip was tested using water as a liquid propellant and vaporization was achieved at 7 W electric input power.

I. INTRODUCTION

There currently exists a strong interest within the aerospace community for micropropulsion devices capable of delivering very small thrust values and low impulse bits for engine sizes and masses orders of magnitude smaller than available with current technologies[1]. Within the National Aeronautics and Space Administration (NASA), the reason for this interest can be found both in the drive to explore the feasibility of microspacecraft designs[2], typically viewed as spacecraft having wet masses on the order of 10-20 kg and below, as well as the need for fine attitude control of larger spacecraft, such as those envisioned for space interferometry missions[3].

One of the most challenging aspects of both types of missions, microspacecraft and interferometry, is attitude control. Either due to the low mass of microspacecraft, or the stringent pointing requirements of spacecraft used in an interferometry constellation, very small impulse bits may be required, which could reach into the micro-Newton-sec to tens of micro-Newton-sec range. While there is available today propulsion hardware to deliver such small impulse bits, namely pulsed plasma thrusters (PPT) or Field Emission Electric Propulsion (FEEP) devices, these thruster types may not fit every mission need in the aforementioned two categories. In view of microspacecraft applications, for example, state-of-the-art hardware is still quite heavy and large, although efforts to miniaturize these technologies are underway.

A new micropropulsion concept was recently introduced, aimed at providing very small thrust values and impulse bits at extremely low thruster weight and size and is the subject of this study. The concept was termed a Vaporizing Liquid Micro-Thruster[4] (VLM) and relies in its construction on silicon-based microfabrication (MEMS - Microelectromechanical Systems) methods. The concept is shown in Fig. 1, and a completed chip is shown in Fig. 2. The VLM operates by vaporizing a

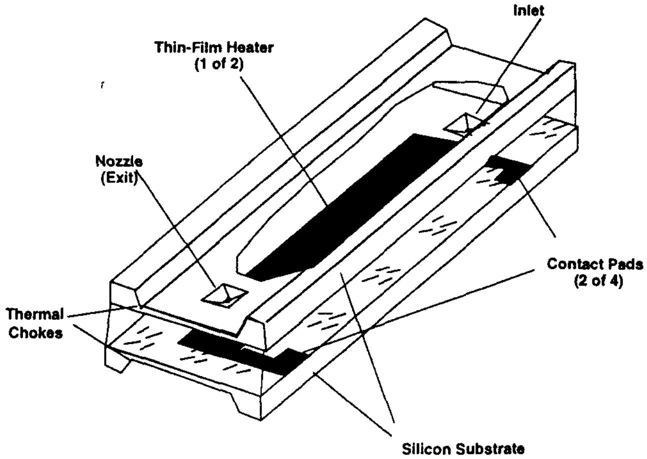

Fig. 1: Concept of the Vaporizing Liquid Micro-Thruster

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Fig. 2: Vaporizing Liquid Micro-Thruster Chip

liquid propellant inside a micro-machined, thin-film deposited heater arrangement. Using liquid, rather than gaseous propellants, reduces leakage concerns commonly found in high-pressure cold gas systems. In addition, liquid propellants allow for more compact storage. Both issues weigh particularly heavily in view of microspacecraft applications since these craft will be severely mass and volume constraint, an will not be able to afford substantial propellant leak rates due to the limited onboard propellant supply.

Their small size and weight, while essential to microspacecraft applications, may, however, benefit larger-scale spacecraft as well. The ability to provide very small impulse bits, thus allowing for very fine attitude control, may, for example, eliminate the use of reaction wheels commonly used for fine attitude control applications. Since these wheels are typically heavy and power consuming, replacing them with a batch of microfabricated thruster chips may result in net spacecraft weight savings, in particular if a propulsion system is already onboard the spacecraft for coarse attitude control or trajectory corrections. Since the VLM relies on the vaporization of propellants, it in principle exhibits quite a degree of flexibility regarding its propellant use, although individual material compatibility issues will always need to be investigated. This flexibility in the use of propellants may make it easy to integrate with other propulsion systems onboard. Finally, the extremely small size and weight of these thruster chips may allow for a multiply redundant attitude control system, thus increasing the overall reliability of the system.

This paper will discuss ongoing development efforts on the VLM concept. In particular, recent proof-of-concept tests, leading to the vaporization of water propellant inside the chip in a laboratory bench-top set-up, will be reported on.

II. VLM DESIGN

The VLM concept in its current form consists of a laminate of three chips, as seen in Fig. 1. The top and bottom wafer contain the vapor deposited thin-film heaters. They are bonded into a stack via a spacer wafer. This spacer wafer features a cut-out that forms the sidewalls of the flow channel as well as vias needed to contact the lower heater element, since electrical contacts are only made from one side of the chip. Flow entering the chip through the inlet, shown at the bottom of the chip stack in Fig. 1, will enter the flow channel formed by the two heater sections and the spacer, and then exit the nozzle. As the liquid propellant flows through the heated channel, it will vaporize and exit the chip in a gaseous phase. The channel has a width of 0.7 mm and a height of 0.6 mm. Channel inlet and nozzle a square-shaped following the anisotropic etch patterns of 100-silicon wafers and have throat dimensions of 100 x 100 μm^2 for the inlet and 50 x 50 μm^2 for the nozzle throat. The nozzle is symmetric with respect to its converging and diverging sections and since the silicon wafer, into which the nozzle was machined is 0.6 mm thick, length of the diverging (and converging) nozzle section is 0.3 mm.

Water is used as a propellant in initial laboratory tests for ease of use and safety reasons. Other propellant choices are ammonia, having a heat of vaporization about half that of water, or, potentially, hydrazine because of its already extensive use onboard spacecraft. Hydrazine use is still uncertain, however, due to materials compatibility issues with typical MEMS materials used in the construction of the VLM chip. Quite likely resistant coatings, such as silicon oxide, will have to be used in order to enable hydrazine operation.

Compared to earlier chip versions, the VLM used in this study had to undergo one significant design change from versions described earlier[4]. In those earlier versions of the chip, a Pyrex wafer had been used to form the spacer chip in the center of the stack. Using Pyrex allows for anodic bonding of the silicon-Pyrex-silicon wafer stack, which is a standard bonding technique used in the MEMS field and yields superb bond strengths. In order for this process to work, extremely smooth surfaces are required. When receiving fabricated spacers from our vendor, however, it was found that surface roughnesses were unacceptable and obtained bond strengths were poor. Polishing attempts of the Pyrex spacer failed and led to repeated wafer breakage, likely due to internal stresses created inside the Pyrex spacer as a result of the ultrasonic drilling of a multitude of holes per wafer. Repeated attempts by the vendor to deliver a satisfactory product failed and, finally, this technique was abandoned. Subsequently, a new technique to fabricate the chip, without allowing for a major re-design due to cost and schedule concerns, had to be devised.

In our newer chip designs a silicon spacer was used instead of the Pyrex spacer. The through-holes fabricated into the silicon spacer are machined using a newly available deep Reactive Ion Etching (RIE) technique, allowing for the machining of almost perfectly straight wall sections in silicon. The same technique was used to fabricate micro-isolation valve chips and the technique is thus described in greater detail in a companion paper[5]. Using Pyrex eliminated the choice of an anodic bonding technique, and new techniques, such as gold-pressure bonding and fusion bonding via silicon oxide layers are being explored. Bonding experiments using a sputter deposited Pyrex layer, in order to allow for an anodic bonding process again, led to unsatisfactory results due to a poor quality of the Pyrex film, and were abandoned. Currently, all our chips feature gold-pressure bonds, however, work on developing suitable fusion bonds continues.

Both gold and polysilicon heaters are being considered in the chip design. The gold heaters will allow for low-voltage requirements, which are desirable in microspacecraft applications, where bus voltages of less than 15 V, or even 5V may be common. On the other hand, polysilicon heaters will allow for fusion bonding of silicon chips (requiring a high temperature anneal that gold heaters would not be able to withstand), and thus provide for higher bond strengths and a higher heat tolerance.

Just opposite the heater strips, a recess has been machined into the silicon substrate, thinning the silicon substrate material at this location. The purpose of this design feature was to provide a thermal choke to reduce heat conduction from the heater surface to the remainder of the chip. However, in order to simplify fabrication, the recess only extended about 300 μm deep into the 600 μm silicon substrate wafer. This allowed the recess to be manufactured in the same process step as the nozzle and inlet. Unfortunately, at this large a thickness the thermal choke proved rather ineffective, as will be seen in Section III, and the design will have to be changed in future versions of the chip.

It is important to achieve complete vaporization inside the thruster since droplets are slow by comparison to gaseous ejections and would thus lower the specific impulse significantly and lead to propellant waste. Achieving his goal poses a major challenge as vaporization has to be accomplished over very small heater lengths (on the order of a few millimeter) in order to be compatible with typical chip dimensions, while at the same time power requirements have to be kept low, anticipating power constraints on a microspacecraft. Furthermore, two-phase flow behavior in micro-channels is still poorly understood, so that performance estimates based on analysis alone currently still result in many uncertainties. Therefore, a proof-of-concept demonstration of the VLM was considered an important milestone.

In the following, ongoing VLM experiments will be described. These tests included thermal characterization of the chip and a proof-of-concept test of the VLM, demonstrating, for the first time, and using water as a propellant, that propellant vaporization is possible inside a VLM chip.

III. THERMAL CHARACTERIZATION OF THE VLM CHIP

Description of Experiment

As indicated in Section II, power availability onboard microspacecraft may be severely limited, not exceeding a few tens of Watts, Thus, any micro-thruster to be used in a microspacecraft will be required to operate within these power constraints. In the case of the VLM thruster, however, within these constraints sufficient heater temperatures will have to be provided to achieve propellant vaporization. Thus, a thermal characterization of the chip, i.e. the measurement of heater temperature vs. input power, is a critical evaluation criterion in the development of such a device. Such a test was performed with a recently completed unit.

In order to perform the temperature measurements the chip was placed under an infrared (IR) camera and power supplied to the chip was measured for a given chip temperature. The thruster temperature could only be measured on the outside walls of the chip, and as a location for the IR camera to lock on, a position in the recess area, just opposite one of the heater elements (compare with Fig. 1) was chosen. A small dot of black graphite-based paint was applied to the chip at this location to provide a surface of well characterized emmissivity for the IR camera. Due to the temperature measurement location, actual heater temperatures may have been slightly higher. However, given a silicon substrate thickness below the heater element of only 300 μm, differences are believed to be small.

Tests were performed with a recently obtained chip featuring a 4 mm long gold heater. This chip was packaged by placing it into a chip carrier, which in turn was bonded via high-temperature epoxy to a nut allowing the device to be interfaced with a flow system at a later stage of the experiment (see Section IV below). It should be noted that this packaging scheme serves initial bench top tests aimed at characterizing the thruster chip performance only. It has the advantage of being cheap and consists of readily available commercial components. Thruster packages more closely resembling flight hardware will likely require customized packaging. To perform a quick test to study the impact of packaging materials and schemes in the short time available for these tests, some chips were placed directly onto a Pyrex block, not using either a chip carrier or attaching nut. The heaters of these chips were contacted directly via probe tips.

All initial tests were performed without water vaporization occurring inside the chip to check the thermal design of the chip independent of the vaporization processes and power requirements associated with them.

Results

Results of the thermal characterization of the packaged chip (4 mm gold heater) are shown in Figs. 3 and 4, presenting electric input power and voltage data vs. heater temperature, respectively. As mentioned above, information on voltage requirements is important for microspacecraft integration purposes. As Fig. 3 indicates, chip temperatures measured reached values of about 100 C at power levels of about 3.5 W electric input power, 150 C at about 5.5 W, and at 200 C this power requirement raises to about 7.5 W. Voltages remain below 5 V for all these cases, as Fig. 4 illustrates. Increasing the power level to 8.5 W yields a temperature of 254 C. These values are higher than those calculated numerically before[4] and are likely a direct result of the heating of the aluminum nut attached to the chip carrier, acting as a heat sink. Although the chip was placed into a ceramic chip carrier, hoping that it would, besides acting as an electric interface, also act as an insulator, improved insulating schemes are obviously required. Additional chips will be packaged using ceramic nuts to act as additional thermal buffers, while at the same time providing the interface to the flow system during vaporization tests.

In the meantime, chips placed on Pyrex blocks were tested. These chips did not feature a chip carrier or attaching nut and heater pads were contacted directly via probe tips. In these cases, heater temperatures of about 90 C were obtained for about 1.2 W, and heater temperatures of 150 C required approximately 2.5 W. One chip was run to about 260 C at about 5 W. These measured values

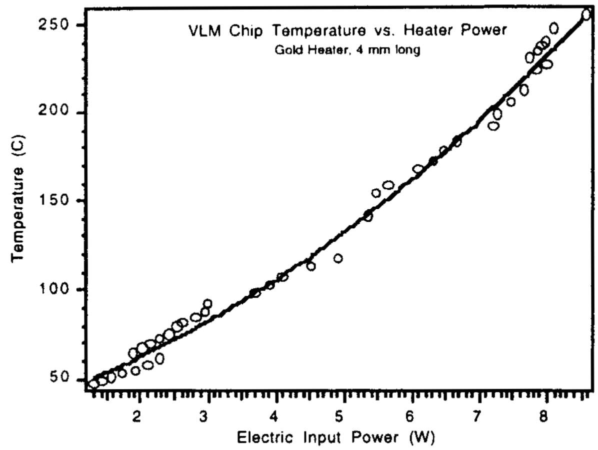

Fig. 3: Chip Temperature vs. Electric Input Power

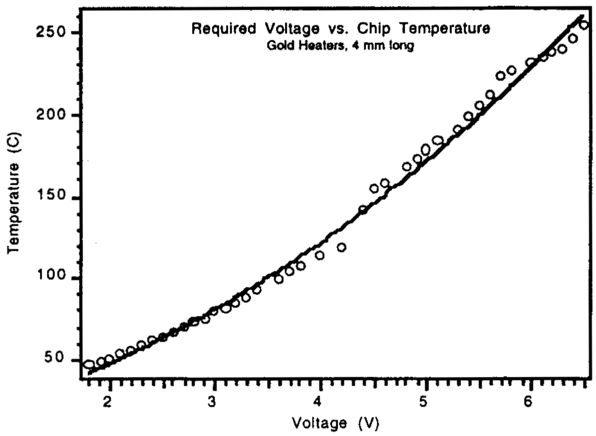

Fig. 4: Chip Temperature vs. Voltage

are much more similar to the numerical data[4], indicating the importance of good thermal insulation. More systematic studies on this issue will be performed in the near future.

Thus, while still within the limits of anticipated microspacecraft power constraints, better thermal performance of the chips is clearly needed and several areas of improvement can quickly be identified, and are to be addressed in future design iterations of the VLM. Packaging, for example, will play a very important role in future VLM assemblies. Unlike the bench-top experiment, thruster chips more closely resembling eventual flight hardware will feature customized packaging, and thermal insulation considerations, as expected, will have to play a very important role in the design. In addition, chip-internal design features may have to be re-investigated. As discussed in Section II, the recess machined into the chip will have to undergo further optimization. If resulting into a more peaked temperature profile near the heater locations of the chip, the comparatively cooler chip periphery should also allow for reductions in heat transfer from the chip.

IV. PROOF-OF-CONCEPT

Using the packaged chip, propellant vaporization tests were conducted. The chip was mounted onto a test rig consisting of a water tank, a small solenoid valve, a filter and the chip assembly. A pressurant supply was connected to the water tank (see Fig. 5). By pressurizing the tank, water could be forced through the valve and filter and into the chip. The exit flow was observed visually in this preliminary set of bench top experiments. The test set-up and procedure was simple in order to allow for a cheap and quick proof-of-concept demonstration. The feed pressure was adjusted to a given level, and water was forced through the chip. Then heater input power was applied and the ejected water jet was observed (see Fig. 5). If no vaporization occurred at power values up to those levels adjusted in the previous thermal characterization tests, the flow rate was reduced by decreasing the feed pressure until vaporization was achieved. The limit on power values below those obtained in thermal characterization tests was imposed to protect the chip from cverheating. Obviously, the water flow will cool the chip, thus, when compared with the "dry" thermal tests, the imposed limitations are conservative.

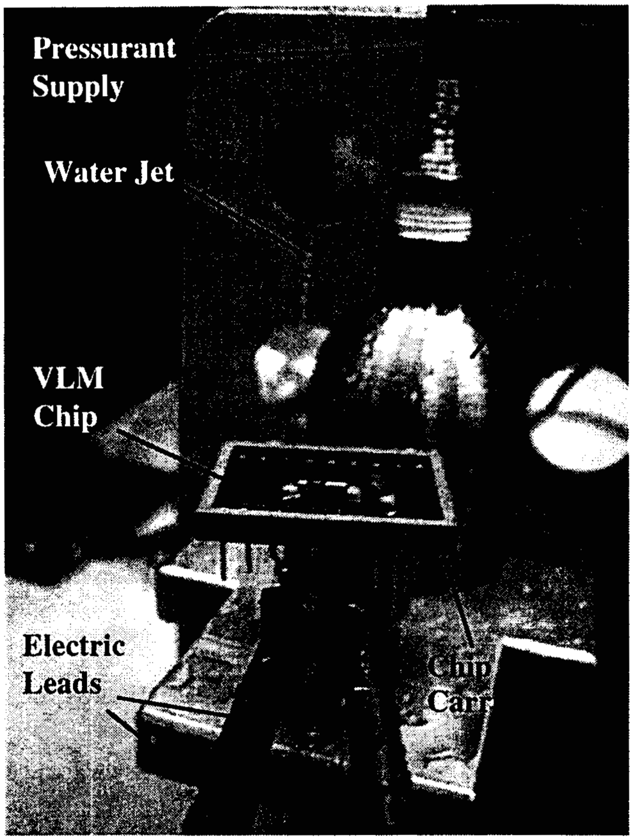

Fig. 5: VLM Chip on Chip Carrier attached to Water Tank. Notice Water Jet Exciting Nozzle. No Heat Input to Chip.

Vaporization of water inside the chip was achieved at power levels of about 7 W at a feed pressure of a mere 0.25 psig estimated. The steam itself was not visible, however, was audible, and in this preliminary set of tests could be verified by condensations on a small mirror. Condensates formed directly over the nozzle region.

The low required feed pressure was not expected. Since the set up was gaged to be used at pressure values of at least several psig, the actual feed pressures required to achieve successful vaporization inside the chip could only be determined with great uncertainty, since at these pressure levels scale readings became inaccurate. Liquid flow rates, while not measurable with the current set-up, were so low that, when in an unheated stage, merely the formation of a droplet could be observed at the nozzle outlet of the chip, rather than the ejection of a jet, as was observed at higher feed pressures (see Fig. 5). Unfortunately, liquid flow rates that low are very difficult to measure and will likely require the development of new diagnostic tools.

While successful vaporization has to be viewed as a major success for this program, the results nonetheless surprised. The ease with which liquid flows could be achieved through the chip was not expected. Concerns with respect to viscous losses through the small chip inlet and flow channel were thus unjustified. The low required flow rates, on the other hand, point to the need for improved vaporization schemes inside the chip, as heat transfer into the liquid appears to be difficult to achieve and only leads to vaporization at very low flow velocities and mass flow rates. Improved flow channel designs, such as shallower channels bringing more fluid into direct contact with the liquid, increased surface roughness (to enhance mixing) or texturing through the use of fins (to increase heater area), may have to be explored. In addition, it is evident that a much better understanding of two-phase flows in micro-channels, both from an experimental, as well as a numerical/theoretical point of view, is required.

V. CONCLUSIONS

A newly proposed vaporizing liquid micro-thruster chip was subjected to proof-of-concept testing. This thruster concept relies on the vaporization of a liquid propellant in a thin film, microfabricated heater arrangement. Use of liquid vs. gaseous propellants will significantly reduce leakage concerns and propellant storage concerns for an operational device.

Thermal characterization of the thruster revealed that approximately 3.5 W are required to achieve a heater temperature of 100 C, 5.5 W to achieve 150 C, and about 7 W to reach 200 C. Heat loss into the chip packaging structure was found to be significant as was determined by comparative testing of chips placed onto (thermally well insulating) Pyrex blocks. In these cases, power values reduced significantly to about 1.2 W for a temperature of approx. 90 C and 2.5 W for 150 C, i.e. about half the values for the packaged chip, pointing to required improvements in the packing area. Although the packaged chip had been placed into a ceramic chip carrier, this type of insulation obviously proved insufficient.

The chip was finally subjected to liquid water flow tests and vaporization of propellant was achieved at about 7 W. Injected flow rates could not be measured with the current set-up, however, appeared extremely low. Water feed pressure had to be lowered to about 0.25 psig in order to achieve vaporization. Higher flow rates would result into heating of the propellant, but not lead to vaporization. The flow conducting abilities of the chip were surprising. While at the outset of the experiments it was expected that large feed pressures were needed to force sufficient liquid through the narrow orifices and flow passages, this was clearly not the case.

It is clear from these preliminary tests that substantial future research work will be required in the heater design. Propellant vaporization rates need to be improved. This may be accomplished by changing the channel dimensions, such as using shallower channel configurations and/or or reducing channel cross sections, allowing more liquid to pass in direct contact with the heater elements. Surface roughness or the insertion of fins into the channel may be investigated to increase mixing as well as heater areas exposed to the fluid. Liquid flow rate measurements at the levels encountered will require the development of new diagnostic tools in this area, since the current experiment appears to have outrun currently available diagnostic capabilities. Most importantly, however, it became clear that a much better understanding of two-phase micro-channel flows will be required than is currently available. A good understanding of such flows would provide a much more solid basis for future design iterations of the VLM chip.

VI. ACKNOWLEDGMENTS

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